Plasma Collective Effects and Radiation Emission from Rotating Collapsed Stars

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Abstract

A non-thermal mechanism, relating the radiation emission to the rotation of a collapsed star surrounded by a relatively dense plasma in the star strong magnetic field, is presented. The fundamental role in the process is played: (i) by the electric field component parallel to the magnetic field lines which is allowed by the large anomalous plasma resistivity; (ii) by the scattering, for instance due to plasma collective effects, of the electron parallel energy and momentum into transverse (to the magnetic field) energy and momentum. Then an explanation of pulsar emission and a model for x-ray sources are proposed. A mechanism for the acceleration of high energy cosmic rays is also suggested.

I. Introduction

Among the most striking features of pulsar emission are the sharpness of the period and, in many cases, the constancy of the pulse characteristics. These facts strongly support the idea that the emitting region is remarkably small and stable.[1] Since the discovery of the two pulsars PSR0833 and NP0532 in remnants of supernovae,[2,3] it has been generally accepted that pulsars are associated with collapsed objects, which are most likely to be neutron stars.[4] Particularly significant for NP0532 is its optical identification with the star that Baade and Minkowski suggested[5] as the collapsed core of the Crab Nebula, following the original supernova theory advanced by Baade and Zwicky.[6]

On the basis of evidence available at present from laboratory plasmas, we propose a plasma mechanism to account for the most evident physical characteristics of pulsar emission, including the production of x rays and the acceleration of high-energy particles. We shall make special reference to the best known pulsar (NP0532) in the Crab Nebula and also suggest an application of the same model to x-ray sources.

II. The Plasma Emission Model

Following the arguments proposed by previous authors,[4] we assume that the condensed stars associated with pulsars are strongly magnetized and rapidly rotating, as a consequence of gravitational collapse and of angular momentum and magnetic flux conservation. We use the rotation as the timer for the pulsation mechanism and as the principal energy source for the emission process. In order to be consistent with the observation of periodically spaced radiation pulses, the magnetic field is assumed not to be symmetric about the axis of rotation, for example, a dipolar or quadrupolar type with its principal axis not aligned with the axis of rotation. The star is assumed to be surrounded by a relatively dense plasma supported by the magnetic field as indicated by the approximate equilibrium equation[7]

$$e\underset{\sim}{E}_{\perp} \left(Z - \frac{n_e}{n_i}\right) + eZ \left(\underset{\sim}{u}_{i\perp} - \underset{\sim}{u}_{e\perp}\right) \times \underset{\sim}{B} + m_i \left(\underset{\sim}{g}_{\perp} - \underset{\sim}{u}_i \cdot \nabla \underset{\sim}{u}_{i\perp}\right) = 0 \tag{1}$$

Here n_e and n_i are respectively the electron and ion density, Z is the ion charge number and m_i its mass; $\underset{\sim}{g}_{\perp}$ is the perpendicular component of the gravity acceleration; $\underset{\sim}{B}$ is the magnetic field; $\underset{\sim}{E}_{\perp}$ is the electric field (*) transverse to $\underset{\sim}{B}$; and $\underset{\sim}{u}_{i\perp} - \underset{\sim}{u}_{e\perp}$ the relative velocity of the ions with respect to the electrons in the same direction. The charge separation $Z - n_e/n_i$ is very small as we shall see and, in virtue of the high magnetic field, its effect, which will tend to prevail over that of the gravitational and centrifugal force, is compensated by a very slow drift of the ions relative to the electrons.

We now recall that, according to Baym et al.,[8] in a highly condensed star superconductivity can occur; therefore, the magnetic field cannot diffuse across it, but co-rotates rigidly. Then, if we consider the region inside the light cylinder, where $\omega_o r < c$, r is the radial coordinate – the effect of electron

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(*) as seen in an inertial frame

inertia is negligible and the electrons are rigidly tied to the magnetic field lines and to the star rotation.

We will use from here on the indices $\perp$ and $\parallel$ to denote components perpendicular and parallel to the magnetic field. Therefore in an inertial frame there will be an electric field $E_\perp$ given by:

$$\underset{\sim}{E}_\perp \approx -\underset{\sim}{u}_o \times \underset{\sim}{B} \tag{2}$$

where $\underset{\sim}{u}_o = \underset{\sim}{\omega}_o \times \underset{\sim}{r}$ is the rotation velocity. In view of the expected low values of $J_\perp$ (the transverse current density) the resistive contribution of the term $\eta_\perp J_\perp$ is considered to be small, η indicating the electrical resistivity. In general there will be also a parallel electric field $E_\parallel$ in a corotating frame, so that the Poisson's equation is:

$$-\nabla_\parallel E_\parallel = \nabla \cdot (u_o \times B) + 4\pi\, e\, n_i (Z - \frac{n_e}{n_i}) \tag{3}$$

where $e(Zn_i - n_e)$ is a residual charge separation whose magnitude will not affect appreciably our considerations. This electric field generates a current along the B lines and is related to it by a large anomalous[9,10,11] resistivity η_{an} that is mainly due to interaction between particles and plasma collective modes rather than to electron-ion collisions,

$$\underset{\sim}{E}_\parallel = \eta_{an} \underset{\sim}{J}_\parallel \quad , \tag{4}$$

where $\underset{\sim}{J}_\parallel = -e\, n_e \underset{\sim}{u}_{e\parallel}$ (the ion current is negligible). We shall discuss the evaluation of anomalous resistivity eventually and recall that this arises because of the strong plasma turbulence that is excited when the electron flow velocity $u_{e\parallel}$ exceeds certain critical values.

First, we notice, as pointed out in [12], that in the case of the Crab Nebula pulsar $\omega_o = 2 \times 10^2$ rad/sec and B at the star surface is likely to be $\simeq 10^{12}$ G, so that at this surface ($r = R \sim 20$ km) we have

$$E_{\perp} \approx 4 \times 10^{12} \text{ V/cm} \quad . \tag{5}$$

It is evident that, even if $E_{\parallel}$ is a small fraction of $E_{\perp}$, particles can be accelerated along the magnetic field lines by a field that is much larger than that of gravitation.

Second it is important to realize that mildly relativistic electrons ($\gamma = \varepsilon/mc^2 \simeq 1$) lose their perpendicular (to $\underset{\sim}{B}$) energy by cyclotron radiation with maximum power at frequencies

$$\omega \approx \Omega_e = 1.76 \times 10^7 \text{ B sec}^{-1} \quad .$$

The time scale of energy loss from an electron is

$$\tau \simeq 2.58 \times 10^8 \text{ B}^{-2} \text{ sec} \quad .$$

For a value of $B \approx 10^{12}$ G, we have $\Omega_e = 1.76 \times 10^{19}$ sec^{-1} (x-ray band) and $\tau \approx 2.58 \times 10^{-16}$ sec. Clearly, this energy loss does not contradict Eq. (1) and does not force the plasma back to the stellar surface, contrary to the conclusions given in ref. 13.

Third, it is possible to transfer transverse energy again to the electrons via plasma collective effects maintained by the parallel electric field. This process is well-known in plasma physics, and has been the object of recent theoretical works.[10,14] In the presence of a plasma wave with frequency ω, a particle-wave resonance occurs that leads to the energy exchange.[10,15]

$$\hbar\omega + \Delta\varepsilon_p = 0 \quad , \tag{6}$$

where $\hbar\omega$ is the energy of the excited mode and $\Delta\varepsilon_p$ is the exchanged particle energy. Now $\Delta\varepsilon_p = \Delta\varepsilon_{\parallel} + \Delta\varepsilon_{\perp}$, with $\Delta\varepsilon_{\parallel} = m_e \underset{\sim}{v}_{\parallel} \cdot \Delta\underset{\sim}{v}_{\parallel}$ and $\Delta\varepsilon_{\perp} = n_o \hbar \Omega_e$ (Ω_e = electron gyro-frequency), and n_o is an integer. The momentum balance equation is

$$\hbar\underset{\sim}{k} + \Delta\underset{\sim}{p} = 0 \quad , \tag{7}$$

where $\underset{\sim}{k}$ is the mode vector, and $\Delta \underset{\sim}{p}$ the exchanged particle momentum. Again, we have $\Delta \underset{\sim}{p} = \Delta \underset{\sim}{p}_{\parallel} + \Delta \underset{\sim}{p}_{\perp}$, with $\Delta \underset{\sim}{p}_{\parallel} = m_e \Delta \underset{\sim}{v}_{\parallel}$, and $\Delta \underset{\sim}{p}_{\perp}$ is taken up by the magnetic field. The resonance condition is then:

$$\omega + n_o \Omega_e - k_{\parallel} v_{\parallel} = 0 \quad . \tag{8}$$

For $\omega \approx \omega_{pe}$ (the electron plasma frequency) and

$$\omega_{pe} < \Omega_e \quad , \tag{9}$$

Eq. (8) then shows that the actual energy exchange with the wave is negligible.

Fourth, since a plasma wave with $\omega \approx \omega_{pe}$ exists (i.e., is not heavily damped) only if $\omega_{pe} > k_{\parallel} v_{the}$, v_{the} being the electron thermal velocity, we see that the electrons participating in the resonance (8) have to be well superthermal. Therefore the electron distribution f has to possess a sizeable tail of superthermal electrons, as is expected in the presence of longitudinal fields $E_{\parallel}$ larger than the critical runaway field E_{run} (see Fig. 1). We recall that E_{run} is the field for which the electron flow velocity, as limited only by electron-ion collisions, would reach the electron thermal velocity. So a typical "runaway" distribution is a Maxwellian with a long tail of relatively few fast electrons. This is a common situation for laboratory plasmas in a strong magnetic field and with an electric field $E_{\parallel}$ applied along it.[16] Notice that in our case $E_{\parallel}/E_{run}$ will be a function of r and we expect that the regime where $(\partial f/\partial v_{\parallel})_{v_{\parallel} = \Omega_e/k_{\parallel}} \neq 0$, as indicated in Fig. 1, be also localized in space.

The result of the interaction described above is a decrease of longitudinal energy of the electrons, and an increase of their transverse energy.

In addition to or instead of this mechanism, pitch angle scattering of the fast particles can be provided by simple collisional effects, which, given the high density values under consideration, are bound to play an important role.

The transverse energy is then emitted in the form of cyclotron radiation and the power output is evaluated by considering the fraction n_E/n of superthermal electrons, whose total density is $n_s \gg n_E$, which at any one time are provided with perpendicular energy.

Therefore

$$w = 3.08 \times 10^{-15} B^2 n_E \text{ erg/(sec}\cdot\text{cm}^3) \tag{10}$$

is the emitted power density at $\omega \sim \Omega_e$. Notice that a ratio of $n_s/n \approx 10^{-2}$ is commonly obtained for $E_\parallel \approx E_{run}$ in laboratory plasmas.[17] For the case of the Crab Nebula pulsar the total power emitted is $W \sim 10^{36}$ erg sec^{-1}, mainly in the x-ray frequencies. With $B \sim 10^{12}$ G and assuming that the emitting region is a shell of thickness δ above the stellar surface (R = 20 km), we would need:

$$n_E \approx 6.6 \times 10^{12} \delta^{-1} \text{ cm}^{-3} \quad , \tag{11}$$

i.e., $n_E \approx 6.6 \times 10^{11}$ cm^{-3} if $\delta \approx 10$ cm, as it was suggested on the basis of dispersion measurements of radio pulses.[18]

Referring to the Maxwellian part of the distribution, we shall assume an electron temperature $T_e \approx 10^6$ °K, in agreement with a commonly accepted estimate of the temperature at the surface of a neutron star,[19] and a density $n \approx 10^{20}$ cm^{-3} so that a cutoff at the plasma frequency of the optical radiation may be possible, in order to explain the high peaks of pulsed radiation observed in this band as we shall later see. Under these conditions, the classical resistivity caused by ion-electron collision is

$$\eta_{cl} = 1.65 \times 10^{-7} [T_e \text{ (kev)}]^{-3/2} \ln \Lambda \quad \text{Ohm-cm} \ , \tag{12}$$

where $\ln\Lambda = 32.8 - 1.15 \log_{10} n + 3.5 \log_{10} T_e$ (keV). For the chosen values of n and T_e, we obtain $\ln \Lambda \simeq 6.3$ and $\eta_{cl} \simeq 3.3 \times 10^{-5}$ ohm-cm. We notice that the corresponding runaway critical field is

$$E_{run} \approx \eta_{cl} n_e e\, v_{the} \approx 3 \times 10^6 \text{ V/cm}, \tag{13}$$

and in our case we expect $E_{\parallel} \gtrsim E_{run}$. Notice that for $E_{\parallel} \ll E_{\perp}$ and $n_e \approx 10^{20}$ cm^{-3} the relative charge separation appearing in Eqs. (1) and (2) is of order 10^{-9}. Under these conditions, it is well-known[20] that the actual plasma resistivity can be orders of magnitude higher than that quoted above, as a result of wave-particle interactions that transfer parallel energy and momentum into transverse energy and momentum and of other processes[11] associated, for instance, with ion-sound or two stream type instabilities. By considering only the former process one can argue that the actual resistivity is of the order of

$$\eta_{an} \approx \eta_{cl}\, f\left(\frac{\Omega_e}{\omega_{pe}}\right), \tag{14}$$

where f is a fast growing function of Ω_e/ω_{pe}.[10] So if $B \simeq 10^{12}$ G and $n_e \simeq 10^{20}$ cm^{-3}, $\Omega_e/\omega_{pe} \simeq 3 \times 10^4$, and there is little difficulty in building up a large resistivity and then accepting the existence of a large electric field $E_{\parallel}$ at the equilibrium. Notice that the condition $\nabla \cdot \underset{\sim}{J} = 0$ inferred by the equilibrium gives $\nabla_{\parallel} E_{\parallel} = J_{\parallel} \nabla_{\parallel} \eta_{an} - \eta_{an} \nabla_{\perp} \cdot \underset{\sim}{J}_{\perp}$, and in view of its dependence[10,11] on B, the term $\nabla_{\parallel} \eta_{an}$ is certainly $\neq 0$.

As in laboratory experiments, there will be also few "fugitive" particles that are able to undergo a full acceleration process and remain unaffected by classical and effective collisions due to plasma collective phenomena.[16] So the presence of electric fields $E_{\parallel}$ would also provide a mechanism for particles to attain very high energies and contribute to the high energy tail of cosmic rays.[21]

III. Application to the Pulsar Problem

We point out once more that the emission and acceleration process previously described is energetically sustained by the star's rotation, which is the largest energy source. As many authors have proposed,[4] in the case of the Crab Nebula pulsar the rotational energy is likely to amount to ~ 10^{48} erg, if $\omega_o = 2 \times 10^2$ rad/sec and I (moment of inertia) ~ 10^{44} gm/cm^2. Therefore the present emission rate could be maintained for ~ 10^5y. We also notice that all of the conditions required for the occurrence of our mechanism are satisfied quite close to the stellar surface. This will then ensure the perfect co-rotation of the emission region and therefore the stability of the pulse period and shape, which are the most important requirements for any pulsar theory.

Four more points have to be discussed: the origin of the pulses, the spectrum of NP0532, the lack of optical and x radiation from pulsars other than NP0532, and the slowing down of the period.

1. We have assumed that the considered magnetic configuration does not have its poles aligned on the rotation axis. Thus the emission process that we have outlined is expected to be more efficient in the magnetic polar regions where the magnetic field lines converge. We may recall that magnetic stars show evidence of enhanced activity at the polar regions. Therefore we would expect to observe a stronger signal when these polar regions point toward the Earth during the star's rotation. Bohm-Vitense[22] has, in fact, shown how a dipolar structure can reasonably explain the presence of double pulses and intermediate pulses, when rotation enables us to see both polar regions. By means of a quadrupolar

structure we might also explain composite pulses. We also recall that $\Omega_e >> \omega_{pe}$, so that x-ray frequencies can freely be transmitted through the plasma and we expect to observe the emission from the whole star with enhancement at the poles. In fact, for the Crab Nebula pulsar[23] the detected x-ray pulses are only ~ 5% above the nebula background (that we consider to be significantly contributed by the direct star emission); in addition primary and secondary pulses are comparable in intensity, are quite wide and not well separated.

2. The proposed cyclotron radiation from superthermal electrons in a strong magnetic field can explain the total power emitted by NP0532 in the x rays. The spectrum due to this process alone is expected to have a maximum in the x-ray region, steeply decreasing at optical and radio frequencies, and more slowly decaying in the γ-ray region. On the other hand, present observations suggest an overall spectrum with two distinct maxima: one at radio frequencies, and another at optical or x-ray frequencies[24]. For this we notice first of all that non linear mode-mode coupling[15] would give nonlinear decay toward lower frequencies than the x band, with sufficient efficiency to explain the level of power emitted in the optical and radio spectra. This process is ineffective for extending the spectrum in the γ region, so that no comparable power emission should be observed in this band. In fact the higher harmonics of the cyclotron mechanism give a distribution several orders of magnitudes below the maximum.

With reference to the radio emission we notice that another mechanism of emission is to be related with the low frequency (less than ω_{pe} and the ion gyro-frequency) modes that are induced by the flowing current $J_{\parallel}$. There are several modes of this kind, longitudinal or transverse, with different directions of propagation relative to the magnetic field, which have been theoretically investigated and correlated with the experiments. For instance, one of these is due to a current gradient[25] $dJ_{\parallel}/dr$ and another one, of greater interest, has frequency $\omega \approx k_{\parallel}\sqrt{KT_e/m_i}$ being of ion sound wave type, occurs for $u_{e\parallel} > \sqrt{KT_e/m_i}$, is longitudinal, propagates along the magnetic field lines, and is associated with electron thermal conductivity or Landau damping in the same direction. Modes of this kind can in turn couple to transverse waves with typical frequencies and wavelengths falling in the observed radio spectrum. So we expect a strong preferential emission in the direction of the magnetic axis in accordance with the observation of the optical and radio high narrow peaks of NP0532.[25,27]

3. Thus far, the Crab Nebula pulsar is the only observed pulsar emitting over a wide range of frequencies. All attempts to detect optical radiation from other pulsars have failed. From energy considerations and from results concerning the slowing down of the period it is quite reasonable to conclude that only relatively young pulsars have x and optical radiation, and that this phase has quite a short lifetime. Moreover, since rotation is the source of the emitted energy, we may consider the period as a measure of the

pulsar age. The period of PSR0833 is only approximately three times longer than that of NP0532; nevertheless PSR0833 has only radio pulses. Therefore, although there is no reason to believe that the two pulsars were born with the same physical characteristics, a sharp aging process would have to be considered, followed by a long radio phase. For this purpose, we recall that the existence of the plasma collective effects providing particles with transverse energy was related to the existence of a "runaway" regime; that is, to the presence of a sizeable tail of superthermal electrons with non-zero derivative for $v_\parallel = \Omega_e/k_\parallel$ (Fig. 1) where $k_\parallel \lambda_{De} < 1$, λ_{De} being the Debye length. On the other hand we know that the appearance of this tail is a very sharp function of $E_\parallel/E_{run}$, typically of the form[16]

$$n_s \approx n\, e^{-E_{run}/E_\parallel} \quad ,$$

where E_{run} is given by Eq. (13). We shall assume that this is still so for our model, and that E_{run} is replaced by $(E_{run})_{eff} > E_{run}$ to take account of the effects of plasma turbulence and interparticle collisions. Therefore, radiation emission by our mechanism will take place where $E_\parallel/(E_{run})_{eff}$ is larger than or of the order of 1.

To explain the transition from the case of NP0532 to that of PSR0833, we assume that for the latter star, because of its initial conditions and of aging, which implies slowing down of rotation and probably decrease of T_e, the ratio $E_\parallel/(E_{run})_{eff}$ is no longer sufficinet to maintain an adequate population of fast particles that make the particle-wave resonance represented by Eq. (8) prevail over ordinary Landau damping. This corresponds to the resonance $\omega + k_\parallel v_\parallel = 0$, which generally involves a considerably larger number of particles (Fig. 1). Then we are left with the low-frequency modes that are excited by the current $J_{\parallel}$ produced by the electric field $E_{\parallel}$, whose typical frequencies are in the radio band, as we said above, and whose propagation is strongly correlated with the magnetic field direction. So the resulting transverse waves could be linearly polarized and the highly regular rotation of the plane of polarization during a pulse of PSR0833 (Vela) could be related to the rigid rotation of the magnetic field lines.[28]

4. As we have indicated, the plasma emission is not the only energy loss of the star; in fact, the most efficient loss is probably the magnetic multipole radiation. In fact we can evaluate the dipole[29,30] radiation to be $\sim 10^{38}$ erg/sec for a value of $B_{surf} \sim 10^{12}$G. With reasonable assumptions on the physical parameter of the star, these forms of radiation could explain quite well the lengthening of the Crab Nebula pulsar period, but they seem to be in contradiction with recent experimental work on the second derivative of the period.[31] If these results are confirmed, a quadrupole radiation would appear to be more suitable.[32] Therefore we suggest a rotating magnetic quadrupole radiation emission, which seems to be compatible with a simple geometry and reasonable magnetization densities. We notice that this type of emission is characterized by very low frequencies, and is therefore completely absorbed by the nebula or the interstellar gas surrounding the star.

IV. Discussion

We summarize our conclusions as follows.

1. A sequence of plasma processes, which have been observed through laboratory experiment and theoretically investigated, can account for pulsar and x-ray emission on the basis of the large rotational energy and the high values of magnetic field that are associated with a collapsed star.

2. The considered process for radiation emission occurs close to the star, within the "light speed cylinder" ($R_c = c/\omega_o$), where the particles are rigidly tied to the rotating magnetic field lines. This is important to explain the rigorous synchronism of the pulse sequence for the pulsar emission and the regular pattern of the radiation polarization.

3. The frequency range of maximum emission, for a given rotation frequency, depends on the intensity of the magnetic field, and, therefore, is related to Ω_e -the electron gyrofrequency- and to the ratio $E_{\parallel}/E_{run}$, E_{run} being the critical runaway electric field, which controls the magnitude of the superthermal tail in the electron distribution function. So for the Crab Nebula pulsar, if $B \sim 10^{12}$G, as indirect theoretical results seem to suggest, the maximum of the spectrum can be expected to be in the x-ray region ($\Omega_e \approx 10^{18}$ rad/sec), and no comparable radiation should be detectable in the γ rays.

4. The optical radiation emission is considered to be strongly correlated with the x-emission and resulting for instance from a non linear process of mode-mode coupling (frequency decay) that leads to emission at lower frequencies and with considerably smaller energy output This is consistent with the fact that for the Crab Nebula pulsar, the

ratio of energy emitted at x-ray frequency to that emitted at lower frequencies is large. The emission in the radio band can also be contributed by a similar process, but in addition the contribution of plasma low frequency modes, excited by the current longitudinal to the magnetic field, has to be considered. We also notice that the thick plasma surrounding the collapsed star provides absorption below the plasma frequency for propagation across the magnetic field. Hence, referring to the Crab Nebula pulsar, we expect little absorption for the x rays and considerable absorption for the optical and upper radio bands, that we consider as resulting from a process of frequency decay. Thus we can explain why the x-ray pulses are only ~5% above the general background that we consider significantly contributed by the star emission, are wider than the optical pulses, and are accompanied by a secondary pulse of the same magnitude. On the contrary, the optical and radio pulses, at the upper hand of the radio spectrum, are quite narrow and well above the star background. The lower end of the radio spectrum could instead be attributed to the low frequency modes so that the progressive pulse widening as the frequency decreases may be justified.

5. The sharp transition from a Crab-type pulsar to a Vela-type pulsar, characterized by a shift of the maximum of emission from x rays to radio waves, is interpreted as being due to a decrease of the value of $E_{\parallel}/E_{run}$, which causes the high-energy tail of superthermal electrons to be depleted and the mildly relativistic cyclotron emission in the x-ray region to stop. Under these conditions, only low-frequency modes, driven by the current longitudinal to the magnetic field, survive. Hence, we can expect a strongly enhanced radio emission in the direction of the magnetic axes so that the plane of polarization is strongly referred to the magnetic lines. So during the rotation this plane sweeps across the signal, as observed in PSR0833.

6. We recall that the Crab Nebula appears as an extended x-ray source, whose power is $\sim$ 10 times larger than the pulsed component, and also as an optical and radio source. Many efforts have been made to explain this emission on the basis of synchrotron mechanism by highly relativistic electrons in the nebula magnetic field.[33] The main difficulty in all the models proposed so far is the requirement of a continuous injection of high energy electrons. For this our model provides a relatively small population of electrons which, under the influence of $E_{\parallel}$, are able to escape the effects of interparticle collisions and plasma collective phenomena attaining very high energies ($\gamma \gg 1$). These fast electrons are then slowed down by synchrotron emission while travelling across the nebula and contribute to the extended radiation emission that is observed.

Additional processes of particle acceleration connected with the rotation of a multipolar magnetic field are likely to take place around and outside the "light speed cylinder" ($R_c = c/\omega_o$); in this case both mildly and highly relativistic accelerated electrons can be supplied. So the overall effect of these two principal acceleration mechanisms would be to provide particles for the synchrotron emission from the Nebula on a very large spectrum.

7. The particles that are able to escape the effects of interparticle collisions and plasma collective effects, undergoing almost free acceleration by $E_{\parallel}$ close to the star and are not affected by the nebula, will then contribute to the high-energy tail of the cosmic-ray spectrum. So, the combined high values of rotation and magnetic field of a collapsed star can provide a mechanism for high-energy particle acceleration, with the consequence that a sizable cosmic-ray anisotropy should be present at very high energies.

8. Finally we point out the possibility of interpreting other x-ray sources[33] in terms of rotating collapsed bodies. Observational results on the optical counterpart of Scorpio X1 do in fact suggest that this is actually a neutron star or a white dwarf.[34] Again for Scorpio X1 radio emission is also

detected.[35] Our mechanism could then be correctly applied to the interpretation of point x sources; they would differ from NP0532 mainly for the absence of the regular pulse pattern. This could be due to lack of observations of special regions of enhanced emission, either because no magnetic polar regions are present or because we are never swept by the polar beams. We would then observe the steady emission of x rays and, depending on the plasma density around the star, also radio and optical emission. The absence of a nebula in the vicinity of the star would in these cases make the source be point-like to the observation.

Note: The importance of the frequency Ω_e, in the magnetic field close to a collapsed star, for the pulsar emission process and the consequent prediction of the observation of pulsed x rays from NP0532 were reported by the authors in a paper given at the Meeting on the Physical Aspect of Pulsars (Scuola Normale Superiore, Pisa, Italy, April 1969).

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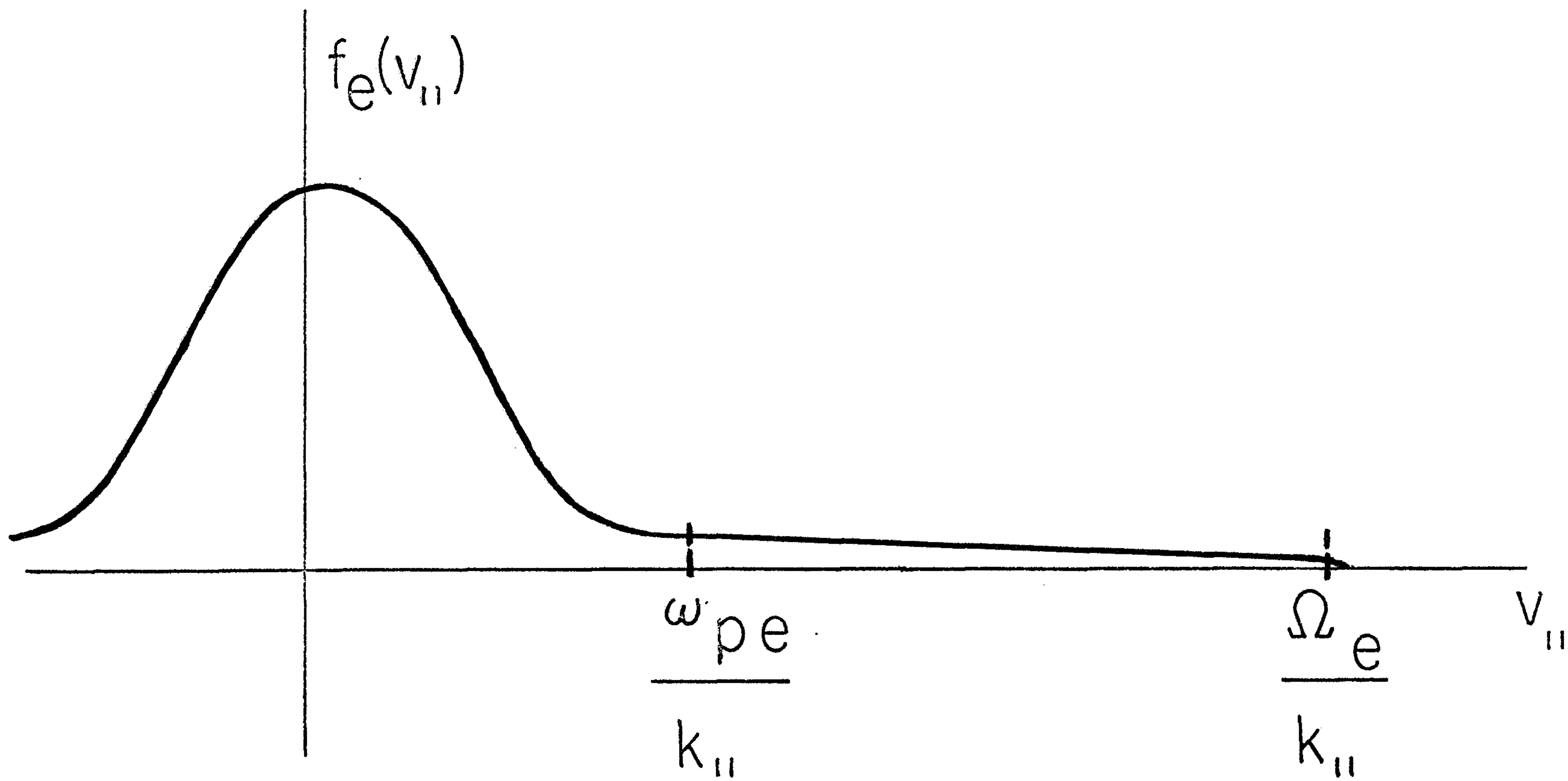

Fig. 1. - Example of a typical "runaway" distribution, with regions of particle-wave resonance indicated.